Safety Assessment of Pile-Founded T-Walls in the Face of Flooding Hazards

Liang Zhang, S.M.ASCE[1]; Lei Wang, M.ASCE[2]; Kevin Turcios-Lovato, S.M.ASCE[3]

[1]Research Assistant, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: liang.zhang@udc.edu
[2]Assistant Professor, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: lei.wang@udc.edu
[3]Research Assistant, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: kevin.turcios@udc.edu

ABSTRACT

Pile-founded T-walls are widely used for levees in New Orleans and other regions of the United States as a key infrastructure for flooding protection. Traditionally, the safety evaluation of pile-founded T-walls follows a simplified deterministic procedure. It is critical to evaluate the performance of the pile-founded T-wall in a probabilistic manner under the potential flooding hazards. This paper presents a study for the safety assessment of the pile-founded T-wall system in the face of flooding hazards using both deterministic and probabilistic procedures. Firstly, the deterministic analysis for the performance assessment is performed using the three-dimensional finite difference modeling. Then uncertainties in geotechnical strength parameters are considered using Monte Carlo simulations and finite difference modeling to evaluate the variability of the performance of the pile-founded T-wall under different flooding hazard levels in a probabilistic manner. The resulting factor of safety curves of pile-founded T-walls in both deterministic and probabilistic manners under various flooding hazard levels are analyzed. It is observed that the mean factors of safety obtained using Monte Carlo simulations are very consistent with the results from deterministic analyses. However, with the probabilistic analyses, the variability of the factor of safety due to input geotechnical uncertainties can be explicitly evaluated. The safety assessment framework is demonstrated through a case study of the pile-founded T-wall design.

INTRODUCTION

Pile-founded T-walls are widely used as a flooding protection infrastructure in the United States. T-walls are T-shape concrete floodwalls supported by batter piles with sheet pile cut off for seepage control. They are especially useful when there is not enough space for expanding the cross-section of levees. T-walls showed robust performance compared to I-walls during Hurricane

Katerina when there were incidences of I-wall failures due to neglected failure modes in the designs (Brandon et al. 2008; Duncan et al. 2008). Some studies have been conducted to investigate the performance of the pile-founded T wall systems using numerical modeling and centrifuge testing (Won et al. 2011; Johnson et al. 2017; Kokkali et al. 2018). However, the coupling between flooding walls, embankment and foundation soil, and reinforcement piles are complicated soil-structure interaction problems and the effects of flooding hazards on the performance of pile-founded T-wall systems have not fully been understood.

Furthermore, for a typical T-wall design project, only limited field investigations were conducted with limited samples of testing data (Duncan 2000; Xu and Low 2006; Gong et al. 2014). The uncertainties in the input geotechnical parameters for the design of T-walls are usually at a high level. To address these uncertainties, a factor of safety is usually applied in the design to achieve a certain level of safety margin. However, the resulting factor of safety could be highly uncertain due to uncertainties in the geotechnical parameters. This paper aims to present a study to evaluate the effects of flooding hazards on the stability of the pile-founded T-wall system using the three-dimensional finite difference modeling and Monte Carlo simulations. It should be noted the scope of this paper focuses on the effects of geotechnical uncertainties on the probabilistic evaluation of pile-founded T-walls. The derived factor of safety curves for different flooding hazard levels in both deterministic and probabilistic manners can provide useful references for risk-informed design and management of T-walls in the face of flooding hazards.

3D FINITE DIFFERENCE MODELING OF PILE-FOUNDED T-WALLS

The finite difference method (FDM) implemented in FLAC 3D was employed to analyze the performance of the pile-founded T-wall system in the face of flooding load. A three-dimensional finite difference model is composed of grid points that form three-dimensional zones and structural nodes that form structural elements. Interface elements are generally used to connect the structural nodes of structural elements to the grid points so the soil-structure interface can be modeled. FDM is a widely acceptable approach to analyzing complex soil-structure interaction problems such as the 3D soil-pile-wall interaction problem. It adopts a finite volume space discretization to solve the Newton's second law using a time finite difference scheme (Reeb 2016).

In the FDM modeling, the Mohr-Coulomb model is used to model the soil behavior for each soil layer and levee fill of the model. The solid brick element is used to model the concrete T-wall with the elastic behavior. The interface elements are applied around the T-wall to model the soil-wall interaction. The H-shape batter piles used to support the floodwall are modeled with pile elements. The pile elements are linear elements with coupling springs to represent the interface between the soil and pile. The coupling springs are modeled with elastic-perfectly-plastic behavior. The initial stiffness and yield point are defined based on the parameters for normal and shear springs of the pile element (Won et al. 2011). The sheet pile is modeled with embedded linear element with interfaces which can consider the potential development of sliding and gap between the sheet pile and soil. The interface is modeled using normal and shear stiffness (k_n and k_s), which are about ten times the equivalent stiffness of neighboring zones. The spring constants are evaluated using the following equations (Itasca 2019):

$$k_s \approx k_n \approx 10 \times [\frac{K + 4/3G}{\Delta z_{\min}}] \tag{1}$$

where $\Delta z_{\min}$ is the smallest width of an adjoining zone in the normal direction, K is the bulk modulus of the soil, and G is the shear modulus of the soil.

For the factor of safety evaluation under different flooding hazards, the strength reduction method is adopted to determine the factor of safety by iteration of finite difference analyses. In the strength reduction method, the strength parameters of soils (cohesion c' and tangent of internal friction angle φ') are artificially weakened in steps until the geotechnical structure collapses. The strength reduction method is implemented in FLAC 3D with a user-defined algorithm to expedite the calculation. In this user-defined algorithm, upper and lower brackets of degree of strength reduction are predefined. With the process of iteration, the upper and lower brackets are updated by the midpoint of the previous range of degree of strength reduction until the difference between upper and lower brackets is less than a specified tolerance. Therefore, the final degree of strength reduction can be efficiently found by using bracketing and bisection. The factor of safety is defined as the ratio of the original input soil strength parameters to the reduced strength parameters at which the model fails. The factor of safety is determined using the following equation (Wang et al. 2018):

$$FS = \frac{\tan(\varphi')_{input}}{\tan(\varphi')_{failure}} = \frac{c'_{input}}{c'_{failure}} \tag{2}$$

EXAMPLE APPLICATION – PILE-FOUNDED T-WALLS

A case study example is used to perform the deterministic and probabilistic performance evaluation for the pile-founded T-wall in the face of flooding hazards. The schematic illustration of the cross-section of the case study is shown in Figure 1, which involves a concrete T-wall with a column and its base, a sheet pile wall (PZ 22), and three rows of batter H-piles (HP 14×73). The top of the T-wall is located at the elevation of EL +3.65 m. The sheet pile wall controls the seepage below the wall and reduces the soil extrusion between the piles. The batter piles in the first row are inclined towards the right side with a 3H:1V ratio while the piles in the other two rows are inclined towards the left side with the same ratio. The spacing between batter piles is 1.5 m in the longitudinal direction (out of plane), which is also the longitudinal width of the finite difference model in the 3D modeling. The geotechnical properties of levee fill and four foundation soil layers are listed in Table 1.

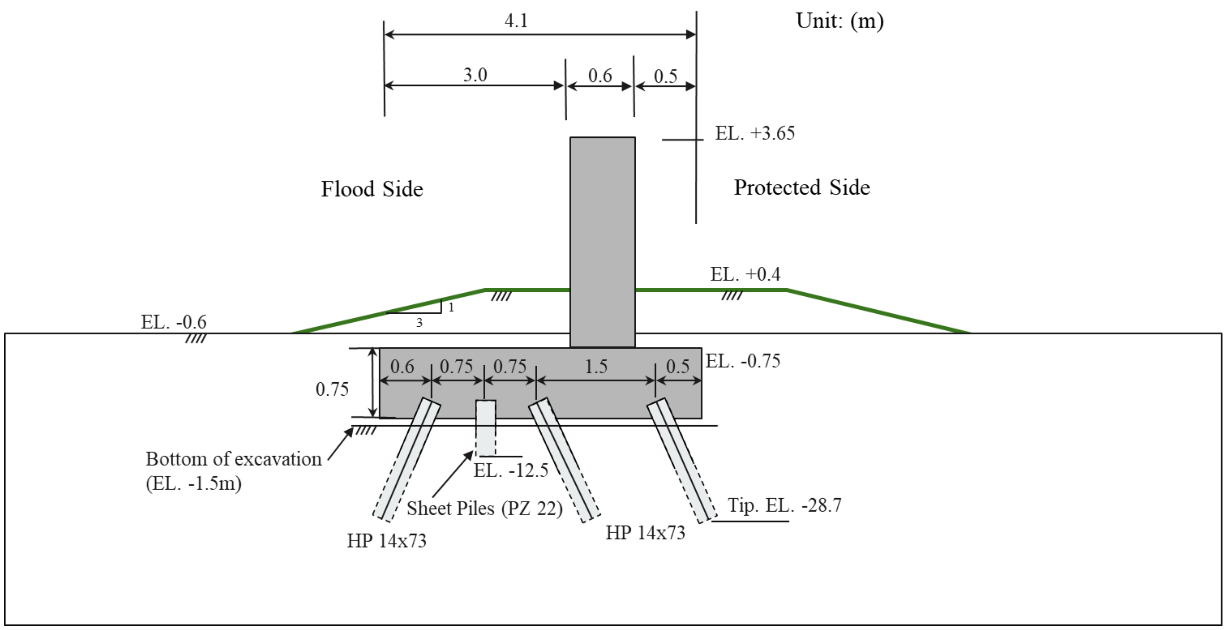


Figure 1. Schematic Illustration of Pile-Founded T-Wall.

Table 1. Soil Properties for the Model

Layer	Top elevation (m)	Soil type	s_u (kPa)	φ (°)	γ (kN/m³)	G (kPa)	K (kPa)
Levee fill	0.4	-	23.9	-	17.3	3585	8.86e4
Peat	-0.6	-	5.7	-	12.6	575	1.42e4
Soft Clay	-4.3	CH	7.2	-	15.7	934	2.30e4
Sand	-26.2	SP	-	30	18.1	7804	1.69e4
Hard Clay	-33.8	CH	46.9	-	18.1	7517	1.85e4

Table 2. Parameters for Normal Spring and Shear Spring of Pile Element

Layer	Elevation (m)		c_n (kN/m)	φ_n (°)	k_n (MN/m²)	c_s (kN/m)	φ_s (°)	k_s (MN/m²)
	Top	Bottom						
Peat	-1.25	-4.3	24.6	11.8	2.0	5.7	0	24.6
Soft clay	-4.3	-26.2	16.8	21.8	2.6	7.2	0	21.8
Sand	-26.2	-28.7	465.3	33.1	54.5	0	22.5	465.3

The soil stratifications and their geotechnical parameters are obtained with modifications from UASCE (2008) and Won (2011), which include a high compressible peat layer to the depth of EL -4.3 m, a soft clay layer (CH) to the depth of EL -26.2 m, a medium dense sand layer (SP) to the depth of EL -33.8 m, and a hard clay layer to the bottom of the model (EL -40 m). The sand layer is the bearing layer of batter piles with pile tips located at EL -28.7 m. The interface parameters for the pile element and structural parameters in the finite difference model are listed in Table 2 and Table 3, respectively. These parameters are representative parameters for the New Orleans levee areas from the UASCE (2008) and Won (2011).

Table 3. Properties of Structural Element in the Model (after Won et al. 2011)

Structures	Element	Structure properties		Interface properties	
Sheet pile	Embedded liner	E	200 GPa	k_n	Eq. (1)
		v	0.3	k_s	Eq. (1)
		Thickness	1.21 m		
		Density	3500 kg/m^3		
Concrete T-wall	Brick element	G	9.6 GPa	k_n	2.12 GPa/m
		K	27.6GPa	k_s	2.12 GPa/m
		Density	2400 kg/m^3	c_i	3.82 kPa
				φ_i	0
H piles	Pile element	E	200 GPa		
		v	0.3		
		Area	0.0138 m^2		
		I_y	3.03e-4 m^4		
		I_x	1.09e-4 m^4		
		I_j	4.12e-4 m^4		
		Perimeter	1.43 m		
		Tip of pile		Area	0.127 m^2
				Q^a	535.0 kN
				K^b	48.0 MN/m
		Head of pile		Area	0.127 m^2
				Q^a	4.2 MN
				K^b	4.4 GN/m

Note: [a] Q is ultimate capacity of end bearing spring.
[b] K is stiffness of end bearing spring.

In the finite difference modeling, the initial stress and strain without the structural components are first calculated. The initialization of the model is performed by setting the strains to zero while keeping the stresses. A similar process is repeated when the T-wall is installed in the model. Then the batter piles and sheet pile are inserted into the mesh, and stresses for the springs are assigned to these elements by an additional run (Won et al. 2011). Figure 2 depicts the finite element meshes in 2D cross section. The hydraulic pressure is applied to both the ground surface and floodwalls on the flooding side (left side of the model). The flood elevation is increased from EL +0 m to EL

+3.0 m with a 0.3 m increment step to model the increasing flood elevation. The groundwater on the protected side is assumed to be located at the ground elevation of the protected side (EL -0.6 m). For the boundary condition of the 3D model, the horizontal displacement of the four side boundary planes of the model is restricted in the normal direction, and the displacement at the base of the model is fixed.

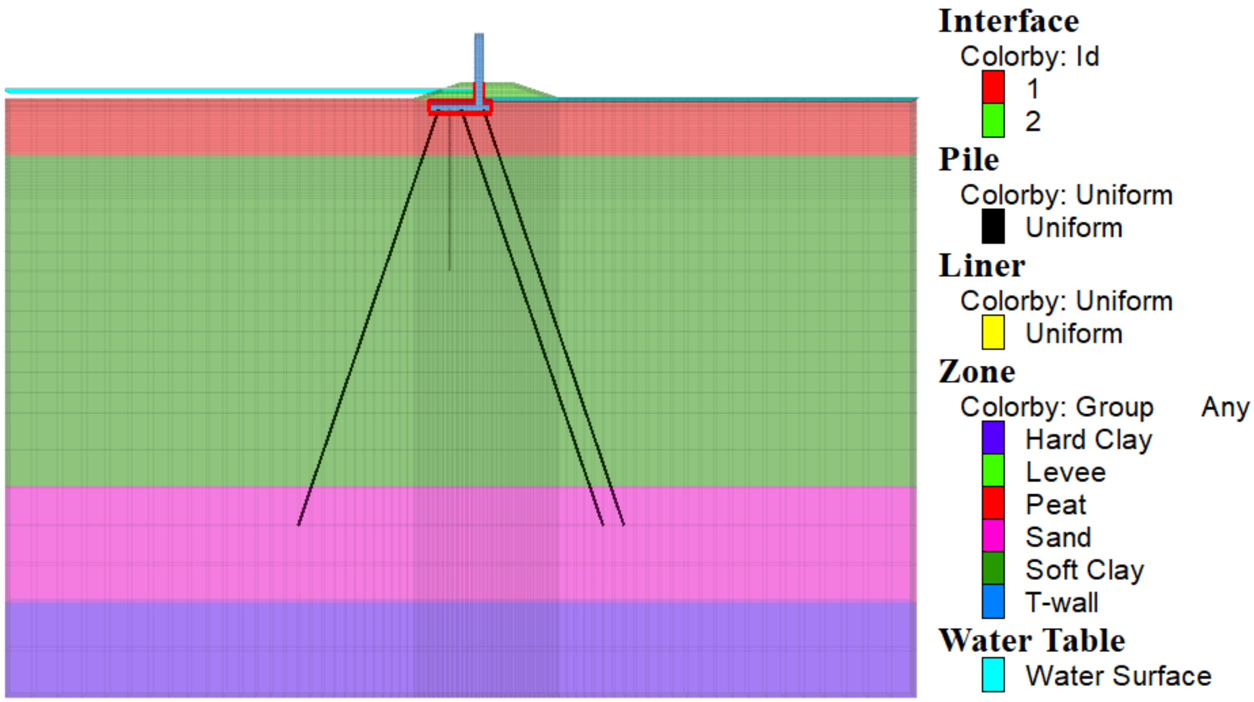
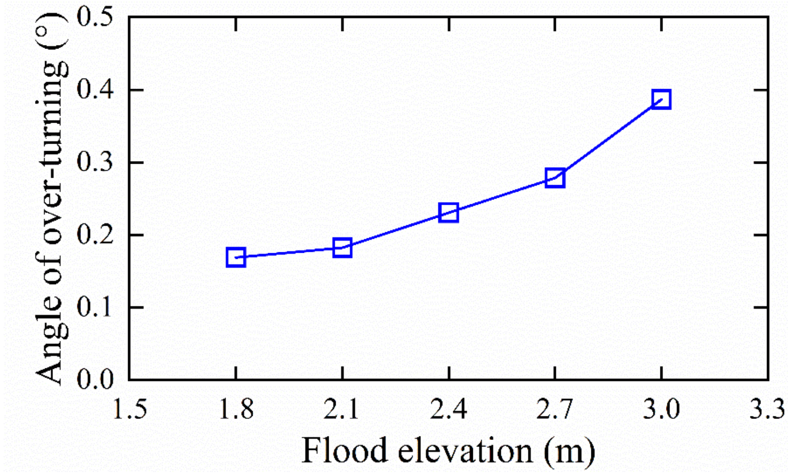


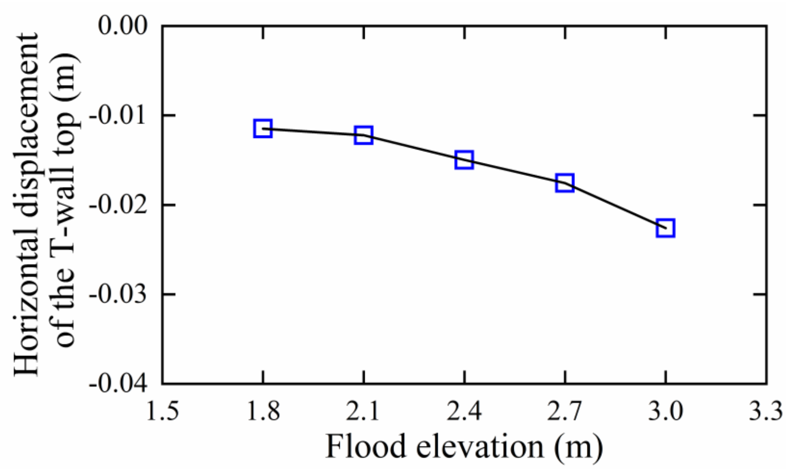
Figure 2. Mesh of Finite Difference Model for Pile-Founded Flooding Walls.

In this study, both deterministic and probabilistic analyses for the performance of pile-founded T-wall system under flooding hazards are studied. The deterministic analyses are conducted by fixing all the input parameters as deterministic values from Table 1 to Table 3. In the T-wall design, there exist three potential failure modes including overturning, sliding, and compression failure of the foundation (FEMA 2012), and all these failure modes are analyzed.

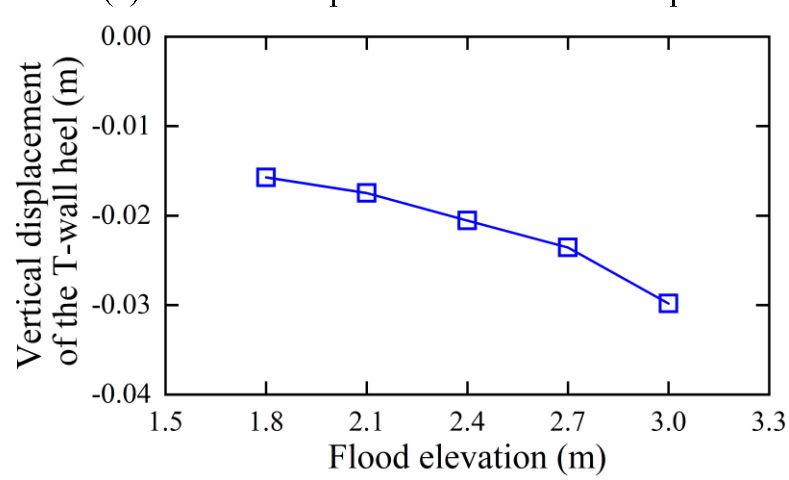
These three failure modes are evaluated by assessing the overturning angle of the T-wall (for overturning failure), horizontal displacement of the T-wall top (for the sliding failure), and vertical displacement at the T-wall heel (for compression failure of foundation). Note that with the increase of the flood elevation, the failure modes can vary. The T-wall might rotate counterclockwise (positive overturning angle) or clockwise (negative overturning angle). The horizontal displacement of the T-wall top might be along the direction from the flood side to landside (positive horizontal displacement) or against that direction (negative horizontal displacement). The vertical displacement at the T-wall heel might be against the gravity direction (positive vertical displacement) or along the gravity direction (negative vertical displacement).



(a) Angle of over-turning



(b) Horizontal displacement of the T-wall top



(c) Vertical displacement of the T-wall heel

Figure 3. Deterministic analyses of three potential failure modes for pile-founded T-walls.

The results of these critical indicators for each potential failure mode against the different flooding hazard levels are illustrated in Figure 3. It can be seen that the magnitudes of the angle of overturning, horizontal displacement of the T-wall top, and vertical displacement at the T-wall heel generally increase with the increase of flood elevation. However, even at the high flood elevation (EL +3.0 m), the likelihood of failure for either of these three failure modes is still very low (with about 0.39° overturning angle, 2.3 cm horizontal displacement and 3.0 cm vertical displacement). In addition, the factor of safety under different flood elevation levels is evaluated using the strength reduction method. The resulting factor of safety curve for the deterministic analyses is illustrated in Figure 4. With the increase of flood elevation from EL +1.8 m to EL +3.0 m, the factor of safety decreases from 5.01 to 2.49, which is consistent with the observations from Figure 3 that the critical indicators for each of the failure modes are at a very low level even with a high flood elevation from a deterministic point of view.

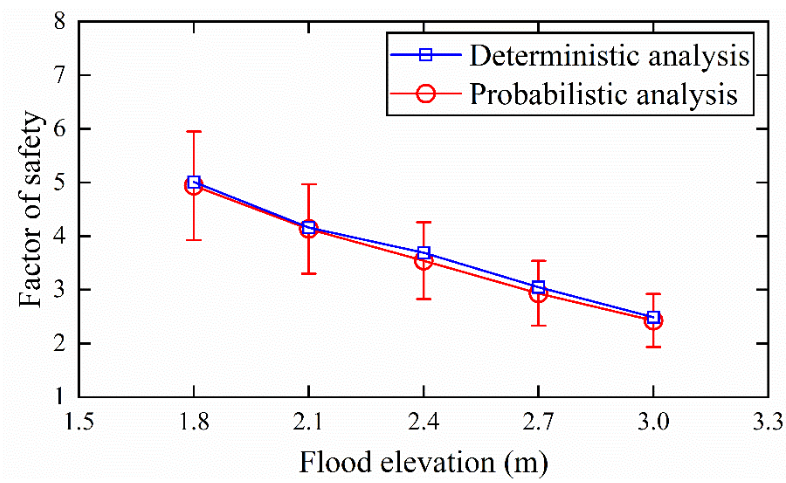


Figure 4. Comparison of deterministic analysis and probabilistic analysis for factor of safety versus flood elevation curves.

However, it is well known that there are significant uncertainties in the strength parameters of soils. For the probabilistic analysis, the undrained shear strength of clay layers and the friction angle of the sand layer are treated as uncertain parameters. The mean values of these parameters are assumed based on the values reported in Table 1, while the coefficient of variation (COV) of these parameters are assumed based on studies published in the literature (Phoon and Kulhawy 1999; Rajabalinejad et al. 2010). In this study, the COV of the undrained shear strength for clays is assumed as 0.3 while the COV of friction angle of sand is assumed as 0.2. In the probabilistic analyses, the Monte Carlo simulations (Ang and Tang 2007) are used to randomly sample all the uncertain strength parameters from their respective lognormal distributions to quantify the effects of variability of soil strength on the performance of the pile-founded T-wall system. The resulting mean factor of safety curve and its one standard deviation bounds under different flood elevations is depicted in Figure 4. It can be observed that the mean factors of safety using Monte Carlo simulations is very consistent with the results from deterministic analyses. However, with the probabilistic analyses, the variability of the factor of safety due to input geotechnical uncertainties can also be evaluated. Furthermore, the potential failure probability of pile-founded T-walls can be assessed, providing a useful reference for stakeholders to make an informed decision for the design and management of pile-founded T-wall systems in the face of flooding hazards.

CONCLUSION

This paper presents a study of safety assessment to evaluate the effects of flooding hazards on the stability of a pile-founded T-wall system. The three-dimensional finite difference method is employed in deterministic analyses to study the effects of flooding hazards on the performance of pile-founded T-wall system. Three potential failure modes are analyzed, and the results are consistent with the factor of safety results obtained using the strength reduction method. Furthermore, the probabilistic safety assessment of the pile-founded T-wall system is conducted using the Monte Carlo simulations combined with finite difference modeling to consider the uncertainties in geotechnical strength parameters. The obtained factor of safety versus flood elevation curves in both deterministic and probabilistic manners can provides valuable information for stakeholders to make a risk-informed decisions for design and management of pile-founded T-walls under the flooding hazards.

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